

REPORT OF THE ADVISORY COMMITTEE IN
SEISMOLOGY¹

The year 1925-26 has been one of noteworthy progress in the study of the zones of movement in California, undertaken by the Carnegie Institution of Washington and the powerful agencies co-operating with it. The purpose of these efforts and the definite plan which has been followed hitherto have been adequately set forth in the earlier reports of this Committee. It is appropriate that this report should indicate some of the more conspicuous results which have thus far been attained, for it is through these that the promise for the future is best appraised.

All of the Annual Reports of the Committee have contained brief mention of the progress of the detailed study of the southern portion of the San Andreas rift, the master fault of California, undertaken by Dr. L. F. Noble, of the United States Geological Survey, and his associates. This deep fault, active, as Dr. Noble has shown, through long periods of geologic time, may prove to be the ultimate source and center of the widespread group of movements which this Committee has set itself to study. The report is therefore of fundamental importance to any study of earth movements in this region and of immediate interest to all American seismologists.

THE SAN ANDREAS RIFT AND SOME OTHER ACTIVE FAULTS IN
THE DESERT REGION OF SOUTHEASTERN CALIFORNIA²

A report is presented herewith of the progress of the author's work during the past six years in mapping and studying some of the faults in the desert region of southeastern California that exhibit evidence of recent movements. This work has included two projects. The first is a study of the San Andreas rift in southern California, and begins with that part of the rift which lies along the southern border of Mohave Desert near the base of the San Gabriel Range and follows the course of the rift southeastward across a part of that range into Cajon Pass. From Cajon Pass it follows the course of the rift along the southern base of the San

¹ Reprinted from *Year Book No. 25*, 1925-26, of the Carnegie Institution of Washington. For previous reports, see *Year Books Nos. 20-24*.

² By Dr. L. F. Noble. Printed by permission of the Director of the United States Geological Survey.

Bernardino Range and through San Geronimo Pass into the Salton Sink. The second project is a reconnaissance of the Mohave Desert, Death Valley, and Panamint Valley regions eastward and northeastward from the San Andreas rift to the Nevada boundary for the purpose of locating and studying the faults which have been active in Quaternary time in this little known region.

The first project was undertaken in 1920, and work was continued on it intermittently for three years. In that time an areal geologic map of about fifty miles of the rift northwest of Cajon Pass was completed. The map covers a strip averaging six miles in width. The rift southeast of Cajon Pass has not yet been mapped and studied. It is planned to do this work in the spring of 1927, and later to prepare a report upon the San Andreas rift for publication by the Geological Survey.

In 1923 attention was shifted to the study of the faults in the desert region east of the San Andreas rift and this study has been continued intermittently since that time, several trips being made into the region each year. On three of these trips the author was accompanied by Professor H. E. Gregory of Yale and on two by Professor W. M. Davis of Harvard. This work has not only yielded much information concerning the active faults of the region, but has resulted in the discovery of many other interesting geologic features, an account of which will be written later. This investigation is still in progress.

The San Andreas rift.—The area of the San Andreas rift already studied in this investigation lies along the southern border of Mohave Desert and extends across a part of the San Gabriel Mountains into Cajon Pass. It reaches from the Southern Pacific track in the vicinity of Palmdale to the Santa Fe track in Cajon Pass. It is shown on parts of the Elizabeth Lake, Tujunga, Rock Creek, San Antonio, and Hesperia topographic sheets of the Geological Survey.

Southeasterly across the area runs a continuously traceable chain of scarps, trough-like depressions, and ridges which afford clear and unmistakable evidence of recent earth-movements. This line of topographic features, which is so straight that one may sight along it for distances of twenty-five miles or more, marks the position of a profound fault in the underlying rocks. This straight and continuous fault is the San Andreas fault—unquestionably the master fault. Bordering the master fault is a belt of roughly parallel branching and interlacing fractures which in places attains a width of six miles. This belt of faults roughly parallel with the main fault will be referred to as the San Andreas fault-zone. The San Andreas fault and the fault-zone together will be referred to in a general way as the San Andreas rift.

Recent features.—The scarps, ridges, and depressions, which form a continuously straight line on the master fault and constitute the so-called "fault-trace," differ in no respect from the similar recent topographic features that mark the San Andreas fault where it has been described in the region north and south of San Francisco. Many of them involve the very youngest alluvial fans and are so fresh that they are entirely unmodified by erosion—in all probability some date from the Fort Tejon earthquake of 1857. It is characteristic of these features that they change abruptly from place to place along the strike of the fault. Within half a mile a scarp may give place to a ridge and the ridge to a trough; or a scarp facing

in one direction may die out and change to a scarp facing in the opposite direction. Other ridges, sinks, and scarps may appear at any place parallel with the main fault-trace. At places these parallel features may occupy a belt as much as half a mile in width. The features differ greatly in size. Some depressions are trenches a few feet wide and a foot or two deep; others are as much as one hundred feet deep and many hundreds of feet wide; many of the depressions are undrained and contain ponds. Some of the features are in rock, others in alluvium. Some ridges are composed entirely of shattered rock—essentially a fault gouge; others are composed of alluvium. At places a ridge may run straight across the mouth of a canyon and block the drainage. The features exhibit all stages of modification by erosion, from those that are still fresh to those that are almost obliterated. In some parts of the rift many subjacent features are entirely buried under alluvial deposits; in other parts they are being exhumed by erosion. Some features involve both the recent alluvium and the older rocks, others involve only older dissected Quaternary beds and older rocks, and still others involve only early Quaternary and older rocks. It is therefore evident that the features are the product of movements that have taken place repeatedly throughout Quaternary time, and that the movements are still in progress. In general the older features are on a much larger scale than the recent ones, indicating that the older movements were of greater magnitude. Some of the oldest features occur several miles away from the main fault, although in general parallel with it.

Some recent features afford clear and convincing evidence of horizontal movement along the San Andreas fault. At a place about three miles southeast of Cajon Pass four deep ravines, that descend the steep San Bernardino Mountain slope east of the fault, are offset abruptly at the fault-trace, each ravine appearing again west of the fault at a point at least 150 feet northwest of the place where it is offset. This feature was discovered by Mr. Peters of Devore, California, who pointed it out to Professor Davis and the author.

The fault-zone.—The belt of branching, interlacing, and roughly parallel faults that borders the main San Andreas fault and constitutes the San Andreas fault-zone exhibits a structure so complex that a simple statement concerning it is difficult to make. In general, the zone is a fault mosaic of elongated sliver-like blocks whose longer axes trend parallel with the strike of the main fault, but at many places the rock masses are so intricately shattered and different formations so mixed together that it is impossible to map them or to determine their relations and age. The evidence of the nature of the fault-movements is somewhat conflicting; the dominant structure is a sort of slicing which appears to be mainly the result of horizontal shear along the San Andreas fault. No exposures of the fault-plane, are obtainable, but the straight course of the fault across an uneven topography suggests that it is nearly vertical. On the other hand, the planes of a large number of faults in the fault-zone are obviously thrust planes, nearly all of which dip southwest at angles ranging from fifty-five degrees to nearly vertical. These structures are the result of thrusting brought about by compressive forces acting from the southwest. Normal faults occur at a number of places in the fault-zone. Some are of considerable magnitude and have high scarps. Graben structures are common in some parts of the zone. The normal faulting, however, is a rela-

tively unimportant feature, probably the result of vertical adjustments within this zone of profound weakness.

One noteworthy feature of the fault-zone is the thorough crushing and shattering of the harder rocks everywhere along the main fault, usually through a belt several hundred yards wide. In this belt the rocks are at most places so ground up that they are practically gouge. At many places the rocks are thoroughly decomposed. Granite, for example, at most places along the fault is so rotten that when wet it becomes plastic like clay.

Another noteworthy feature of the zone is the occurrence of long narrow blocks of granite which form inverted prisms inset in soft Tertiary or early Quaternary beds by faulting in such a way that the fault-planes, which separate the granite from the sedimentary beds, dip under the granite prism from both sides, the apex of each granite prism pointing downward. Some of these granite blocks are a mile long and a quarter of a mile wide. This structure suggests that the granite blocks have been squeezed up by compression. Exposure of granite lying upon Tertiary or early Quaternary beds and separated from them by thrust planes that are almost flat are common in some parts of the fault-zone.

An interesting feature of some of the branching faults of the San Andreas rift is the occurrence along them of narrow strips of steeply dipping Tertiary sediments bordered on both sides by vastly older crystalline rocks. One of these ribbons of Tertiary sediments pinched between the crystalline rocks runs twelve miles through the highest part of the San Gabriel Range and is at most places less than one hundred yards wide. The beds at places are nearly vertical. They lie in a great thrust fault that branches from the San Andreas fault-zone at a low angle and runs nearly parallel with it for many miles. Several cross-faults within the San Andreas fault-zone are marked by similar ribbons of nearly vertical sediments. It is obvious that faults characterized by this structure are profound, indeed.

Although the San Andreas fault runs for some distance near the northern base of the San Gabriel Range, it does not actually bound the range, for it crosses the range at an elevation of 6,800 feet between Rock Creek and Cajon Pass. The initial uplift of the range did not take place upon the main San Andreas fault, but, rather, upon faults that branch from the San Andreas fault-zone. The planes of these branching faults, wherever exposed to observation, are thrust planes which dip steeply southwestward into the mountain mass in such a way that the older crystalline rocks of the range override younger sedimentary rocks at the base of the range.

Areal geology.—Eleven different rock-formations have been recognized in the area studied; two of them are probably pre-Cambrian, one is Paleozoic, one Mesozoic, four Tertiary, and three Quaternary.

The two formations which are believed to be pre-Cambrian are a series of schists and a series of gneisses. Both are largely recrystallized and have undergone profound metamorphism. The schist series is chiefly of sedimentary origin and the gneiss series is of igneous origin. Which is the older is not known.

The schist series is composed chiefly of quartz-sericite-albite schist, which at most places exhibits a distinctive bluish-gray color due to the presence of innumerable tiny flakes of graphite, but it includes many beds of chlorite schist and

actinolite schist, and, in places, beds of metamorphosed limestone (marble) and sandstone (quartzite). This schist series is the so-called "Pelona schist" of Hershey. In all probability it is the correlative of the Rand schist of the Randsburg district, with much of which it is lithologically identical.

The gneiss series is an intricate assemblage or "complex" of banded and contorted gneisses which range in composition from granite and quartz-monzonite gneiss to diorite gneiss. A gray quartz-diorite gneiss is the prevailing rock, but the series includes much amphibolite and in places large bodies of crushed and altered pegmatite and aplite. Both the gneiss series and the schist series are injected by Mesozoic granite and, at places, by quartz porphyry of unknown age.

The only Mesozoic rock represented in the area, so far as known, is granite. This granite extends eastward from the San Andreas rift for great distances over the Mohave Desert region, and is part of a great batholith which is probably of the same age as the Sierra Nevada batholith and may be connected with it. At many places along the rift this granite contains masses of limestone and schist, some of them several miles in extent. All these masses are inclusions in the granite; many apparently represent roof pendants of the batholith.

The Paleozoic rocks are the masses of limestone and schist just referred to. They are always surrounded by and injected with the granite or granite gneiss and are thoroughly altered by contact metamorphism. A few obscure fossils have been found in them by the author—chiefly crinoid stems and corals. The fossils are too badly altered to be specifically determinable, but they are believed to represent Carboniferous forms.

The oldest Tertiary formation is a series of ten sandstones, conglomerates and dark shales which represent the Martinez formation of Eocene age. Nearly 5,000 feet of these beds are exposed on Rock Creek, where they contain typical Martinez fossils. This formation is the youngest marine formation exposed in the area studied, and in fact anywhere in the Mohave Desert, so far as known. All succeeding formations are of terrestrial origin.

What appears to be the next younger Tertiary formation is a series of andesitic and rhyolitic lavas, breccias, and hard red sandstones that may represent the Sespe formation of Oligocene (?) age. No fossils have been found in it and all contacts with other Tertiary formations in the rift are faults. Consequently, its stratigraphic position is unknown.

Overlying the Martinez formation with marked angular unconformity is a series of fanglomerates, arkose sandrocks, and shales, which, near Rock Creek, have an exposed thickness of about 5,000 feet. These beds are particularly well exposed in the Devil's Punchbowl near Rock Creek and in Cajon Pass, where they form great tilted ledges of sandrock, that are familiar to all travelers through the Pass. Vertebrate fossils have been found in them which suggest a stage of the upper Miocene not far from that represented by the Mint Canyon formation of Kew. Accordingly, the beds are here assigned tentatively to the Mint Canyon formation.

The three Tertiary formations just described are in general well consolidated and are profoundly disturbed. Their areal distribution has no relation to the present topography. Obviously, they were deposited before the initial uplift of the

San Gabriel Range and before the movements along the San Andreas rift that resulted in the network of older faults in the fault-zone.

Above the Mint Canyon formation, and separated from it by an angular unconformity, are beds of fine arkose sand, clay, and gravel which may be of late Pliocene age, or of early Quaternary age, or both. Probably they are roughly equivalent to the Saugus formation of Kew. They are well exposed at Cajon Pass, where they overlie the Mint Canyon formation, and at many places northwest of Cajon Pass along the desert border and in the rift. In contrast with the older Tertiary formations they are all poorly consolidated and in general are much less disturbed. They are believed to have been deposited after the initial uplift of the San Gabriel Range and after the older faulting along the San Andreas rift referred to in the preceding paragraph, but before uplifts took place that raised the mountains to their present height. Their deposition appears to have followed a period of erosion which had reduced the land to a fairly mature topography, for the basal beds are composed chiefly of fine material. Along the rift they commonly fill valleys formed by the earlier faulting. A few obscure fragments of vertebrate bones found in the basal beds at Cajon Pass suggest Pliocene forms, but the evidence is not certain. At many places along the rift it is difficult, and, at some places, impossible to separate the beds just described from older Tertiary and from younger Quaternary deposits, owing to the lack of fossils, to the complex structure of the fault-zone, and to the fact that the beds are lithologically identical with beds in the underlying Mint Canyon and overlying Quaternary. Degree of consolidation is not a reliable guide in correlating beds in the rift, for although in a general way the Mint Canyon formation is more firmly consolidated than the later formations, many Mint Canyon beds are as loosely consolidated as Quaternary beds.

The Quaternary deposits comprise at least three formations, all of which are unconsolidated. The oldest formation consists chiefly of fanglomerate, but includes some arkose sand and sandy clay. It overlies the Pliocene or early Quaternary formation just described. In places it is tilted and moderately faulted, but on the whole it is not greatly disturbed. It was deposited after the San Gabriel Range had attained something like its present configuration and height. The next younger formation consists of dissected alluvial fans and terrace remnants and is undisturbed except along the San Andreas fault-zone. Its dissection records the latest uplift in the San Gabriel Range. The youngest formation is the recent alluvium—fan deposits, boulder wash, and soil. It is undisturbed except where involved in the recent movements along the San Andreas fault.

Distribution of rocks along the San Andreas rift.—Very broadly speaking, the San Andreas fault-zone in the area studied is a belt made up of representatives of all the rock-formations just described, bordered on both sides by pre-Tertiary crystalline rocks. The prevailing rocks north of the fault-zone are Mesozoic granites with inclusions of limestone; those south of it are pre-Cambrian schists and gneisses. The Tertiary formations lie chiefly within the fault-zone, where, together with masses of the older and younger formations, they form the complex mosaic of long sliver-like blocks already described. However, for a distance of fifteen miles northwest of Cajon Pass, only crystalline rocks occur in the fault-zone; and at and northwest of Cajon Pass and near Palmdale, Tertiary and

Quaternary rocks extend beyond the zone into Mohave Desert. All Quaternary formations except a few patches of recent alluvium occur either within or north of the zone.

Scarcely anywhere in the fault-zone are the rocks on opposite sides of the master fault similar. This relation is particularly marked in the pre-Tertiary rocks. For example, in a stretch fifty miles long extending from a point six miles southeast of Rock Creek to the Crafton Hills east of Redlands, the fault is bordered continuously on the south by the series of pre-Cambrian schists already described, whereas the rocks north of the fault are Mesozoic granites and pre-Cambrian gneisses. These relations not only show that the movements along the fault have been of very great magnitude, but they strongly suggest that the movements began in pre-Tertiary time.

The distribution of certain Tertiary rock masses along the master fault affords a suggestion that a horizontal shift of many miles has taken place along the rift. On the north side of the fault, near Cajon Pass, a small block of strata lithologically similar to beds in the Martinez formation at Rock Creek is associated with Mint Canyon beds. The only other exposure of Martinez associated with Mint Canyon beds anywhere in the region lies on the opposite side of the fault at Rock Creek, twenty-four miles northwest of the locality in Cajon Pass. At both localities the beds of both formations are so intricately faulted that a displacement of any magnitude is conceivable, and it thus appears possible that horizontal movements along the fault have dragged the rock-masses north of the fault to the southeast in relation to those south of the fault, or have dragged the masses south of the fault to the northwest in relation to those north of the fault. The evidence just cited, however, is not convincing, and it certainly is not definite enough to amount to proof. It is to be hoped that the study of the rift in the region south of Cajon Pass which is planned for this winter will throw more light on the problem.

Broader topographic features.—The San Andreas fault-zone is in striking topographic contrast with the areas bordering it on the north and south. North of the fault-zone a gently sloping alluvial plain stretches far out into the Mohave Desert. This plain is made up of alluvial fans built out from the mountainous region south of the rift. South of the fault-zone lies the high San Gabriel Mountain Range, a part of which is crossed by the rift. Everywhere south of the rift these mountains are characterized by exceedingly rugged, youthful topography. The drainage is insequent, or dendritic, ridges are serrated and irregular, and spurs are knife-edged and sprawling.

The mountain peaks are of different heights and no flat-topped ridges exist. Within the fault-zone the topography is very different. Long, narrow ridges and long, narrow valleys trending parallel with the San Andreas fault are the dominant topographic forms. The ridges have even, gently sloping tops. These even tops of the ridges, many of which are composed of heterogeneous rocks of complex structure, are believed to represent remnants of a peneplain. Near Rock Creek, where the ridges are of granite, they present fine examples of the pan-fan or near pan-fan stage of desert erosion. Some of this pan-fan topography is in process of being exhumed from a cover of Quaternary alluvium.

Even where the rift crosses the San Gabriel Range it is characterized by the

parallel longitudinal valley and ridge topography just described. The high divide where the master fault crosses the range is a gap, or col, that lies midway between Cajon Pass and Rock Creek. The elevation of this gap is a little under 6,800 feet. The recreation camp of the recently opened Los Angeles County Park is situated in this gap. It is reached by a magnificent road that follows the master fault all the way from Rock Creek to Cajon Pass and affords a splendid opportunity to study many recent features along the fault. The divide, or gap, just described is on the axis of a broad upwarp which has bowed up this part of the San Gabriel Range in late Quaternary time. Northwest of this axis of warping the fault-zone slopes northwestward toward Rock Creek, the long parallel valleys and the crests of the long even ridges descending steadily in that direction until, northwest of Rock Creek, many of the older rift features plunge beneath a cover of Quaternary alluvium. Southeast of this axis the fault-zone slopes southeastward toward Cajon Pass, the rift ridges and valleys descending steadily all the way to Cajon Creek. One ridge finally passes under the alluvial filling of San Bernardino Valley.

This downwarp, or rather failure of uplift, in the area about Cajon Pass is one of the factors to which the pass owes its existence. The other factors are faulting, soft rocks, and erosion. Faulting along the San Andreas fault-zone has inset a great mass of soft sedimentary rocks in the hard crystalline rocks about the pass in such a way that the soft sedimentary rocks extend from Mohave Desert through to the main San Andreas fault almost at the edge of San Bernardino Valley. Only a narrow belt of crystalline rocks south of the fault separates these soft rocks from San Bernardino Valley. The downwarp, or absence of strong uplift, by keeping depressed this narrow belt of crystalline rocks already breached obliquely by the San Andreas fault and rendered weak by crushing along the fault, has enabled Cajon Creek easily to maintain its course across the crystalline belt, and the softness of the sedimentary rocks has enabled the creek quickly to excavate in them by headwater erosion the huge amphitheater under the rim of Mohave Desert at the head of the pass. The amphitheater includes all the upper valley of Cajon Creek and its rim is a line of steep southward-facing bluffs, eight miles in length. From the summit of the bluffs an alluvial plain slopes northeastward many miles into Mohave Desert. This alluvial plain is the surface of a gigantic alluvial fan built out northeastward from the high part of the San Gabriel Range, afterward tilted and somewhat disturbed in its upper portion, and then dissected by wide and deep-stream channels running down its slope. No greater surprise awaits the geologist who travels up this fan toward Cajon Pass from the desert than to find that, instead of resting against a mountain slope, the upper part of the fan drops suddenly away at the amphitheater just described—the amphitheater has completely beheaded the fan. The stream valleys on the fan are all truncated headward by the bluff along the head of the amphitheater, so that they appear in cross-section along the summit of the bluff as deep notches. The great width and depth of some of the valleys at the point of truncation is eloquent testimony of the former great extent of the fan beyond the point where it is beheaded. Inasmuch as the fan drains into Mohave River its beheading must have had far-reaching consequences in the Quaternary history of that stream. Altogether, Cajon Pass affords one of the most interesting and spectacular geologic studies in the West.

In brief, the topographic expression of the San Andreas rift in the area studied is not a great scarp bounding a mountain range, but, rather, a belt of long, narrow valleys and ridges which at one place lies along the base of a mountain range but at another place lies across a part of the range; this part of the range has recently been broadly uplifted across the path of the rift.

Geologic history.—Until a study of the rift southward from Cajon Pass shall have been completed it would be premature to attempt a systematic outline of the geologic history. However, an incomplete summary of the probable sequence of events may be given from the evidence at hand.

The distribution of the pre-Tertiary rocks along the rift indicates that movements took place upon it as far back as late Mesozoic or early Tertiary time. The first movements whose date can be established approximately, however, took place at some period between late Miocene and early Quaternary time, because they involve the upper Miocene Mint Canyon formation but not a formation that is believed to be either late Pliocene or early Quaternary or both. These movements were of great magnitude. Apparently they were largely horizontal, although definite proofs of their nature is not yet established. Many of them certainly were thrusts. The initial uplift of the San Gabriel Range is believed to have taken place at some time during this period, not upon the main San Andreas fault, but upon faults that branch from the San Andreas; it was brought about by thrusting from the south, southwest, or west. These movements were followed by a period of erosion which appears to have resulted in peneplanation. Remnants of the peneplain are preserved on the flat-topped ridges of the San Andreas fault-zone. Probably the peneplain is to be correlated with the Ricardo peneplain of Baker. Beds which may be either late Pliocene or early Quaternary, or both, were deposited in depressions in this more or less mature surface. As deposition went on, new depressions were constantly being formed along the rift by faulting. The beds thus deposited continued to be disturbed by fault-movements along the rift, and, at some time in the early Quaternary, the uplift of the San Gabriel Range was renewed. At some period after this uplift, alluvial deposits washed from the slopes of the range may have covered parts of the San Andreas fault-zone and these deposits may have helped preserve the flat tops of the ridges by burying them. Still later in Quaternary time, but before the Glacial Period, the northern part of the San Gabriel Range was bowed up locally in the present high region about Baldy and North Baldy Peaks. This movement was independent of the San Andreas rift, for the rift is gashed diagonally across the axis of uplift and has been raised with it. As a result of the erosion following this last uplift, many of the ridges in the rift in this high country have been considerably dissected.

The different stages of erosion exhibited by the recent, sub-recent, and older topographic features along the rift are proof that faulting has been taking place at intervals all through Quaternary time. The movements are still in progress.

Other faults.—A reconnaissance of the Mohave Desert, Death Valley, and Panamint Valley regions east and northeast of the San Andreas rift was made in eight field trips. On four of the trips the author was accompanied by Professor H. E. Gregory and on two by Professor W. M. Davis. In the course of this reconnaissance we studied three great faults which exhibit evidence of recent

movement—the Garlock fault, the Death Valley fault, and the Panamint Valley fault. The Garlock fault resembles the San Andreas rift. The other two faults are of a different type.

The Garlock fault.—The Garlock fault branches from the San Andreas rift near Tejon Pass, runs northeasterly through the Tehachapi Range to a point near Mohave, and thence northeasterly and easterly along the southern base of the Sierra Nevada and El Paso ranges into the Randsburg quadrangle. This fault was first studied by Hess, who called attention to evidence of recent movements upon it in the vicinity of Garlock and named it the Garlock fault. Recently it has been studied and described in detail by Hulin in the Randsburg region, where it shows evidence of horizontal movement and exhibits many striking recent features. Parts of it west of the Randsburg district have been studied by Buwalda. No information has been available, however, concerning the extension of the fault eastward beyond the Randsburg quadrangle. Accordingly, we undertook to trace the fault eastward from this region where it had been studied, and found that it is traceable for fifty miles east of the Randsburg quadrangle. Its total length is therefore two hundred miles, and it thus constitutes one of the major faults of California.

For many miles east of the Randsburg quadrangle the Garlock fault coincides roughly with a long straight depression which trends east and west and which we have named the Leach Trough, taking the name from Leach Point, a prominent landmark south of a low divide in the trough. The fault is clearly exposed at a number of places along the northern border of the Leach Trough, where it runs along the slopes of the hills facing the trough. It is particularly well exposed at the south end of the Slate Range where it involves Tertiary strata that are probably of late Miocene or early Pliocene age. Other good exposures are found on the roads leading north of the Leach Trough to Hidden Spring and Quail Spring. Eastward beyond the Leach Trough, between Quail Mountain and the border of South Death Valley, recent alluvial deposits mask the geologic structure, but east of this area a fault which continues eastward nearly in line with the Garlock fault is believed to be a prolongation of that fault, although the relation cannot be regarded as proven. This fault bends southeastward and joins at a very low angle a fault that runs northwest and southeast along the axis of the South Death Valley trough. The faults come together at a point near the base of the Avawatz Mountains several miles east of Cave Spring Wash and from that point southeastward the fault line lies along the base of the Avawatz Range.

At most places east of the Randsburg quadrangle the Garlock fault, like the San Andreas rift, separates different pre-Tertiary rocks for long distances. All along the Leach Trough, for example, the pre-Tertiary rocks bordering the fault on the north are schists and gneisses, probably of pre-Cambrian age, whereas the pre-Tertiary rocks south of the fault are Mesozoic granite and a few masses of partly metamorphosed Paleozoic sediments. This granite is part of a great batholith that underlies most of Mohave Desert. In all probability it is continuous with the granite that lies everywhere along the north side of the San Andreas rift in the area that the author has described. Tertiary rocks occur at many places on both sides of the fault and are involved in the faulting. Most of these Tertiary rocks are rhyolitic lavas and tuffs but some are clays, sandstones, and conglomerates.

Probably they represent more than one stage of the tertiary, but all are believed to be younger than early Miocene. Wherever the base of the Tertiary rocks is exposed it rests upon an uneven surface of granite or other crystalline rocks.

The Garlock fault apparently marks a significant structural and topographic boundary in the region. At the fault, or not far north of it, all the north-south structures which characterize that part of the Great Basin lying between the Sierra Nevada and Death Valley come to an abrupt end. For example, the valley of Searles Lake, the Slate Range, Panamint Valley, and the Panamint Range terminate at or not far north of the Leach Trough, as may be seen from an inspection of the Searles Lake topographic map. South of the fault the geologic structures do not exhibit the parallel orientation that they do north of the fault, nor do they trend consistently in any one direction. Consequently, the mountains and valleys south of the fault are irregularly distributed, more or less shapeless in form and haphazard in trend. North of the fault the mountain ranges are high and rugged and the valleys deep. At many places they are bordered by huge scarps along which faulting has taken place in very recent time. The region is characterized by violent topographic contrasts and by many physiographic features of extreme youth. In other words, it is decidedly a region of recent and present instability. The region south of the fault presents a striking contrast to the region north of the fault. The mountain ranges are not nearly so high nor so rugged as they are north of the fault. All of them are of small extent; few are bordered by fresh scarps. Most of the granite ranges are at or near the so-called pan-fan stage of erosion. Indeed, these granite pan-fans are the outstanding physiographic feature of the region south of the fault, and may be said to characterize it. Nowhere else in the desert region of America are they so magnificently displayed, so extensive, or so numerous. In his traverses across this region between the San Andreas rift and the Nevada boundary the author has already counted and mapped fifteen ranges in this pan-fan stage. Many of the pan-fans are almost perfect examples of the hypothetical and of the arid cycle of erosion, the mountains having been reduced to broad gentle domes up which the alluvial fans sweep to the very summit. Not all the mountains exhibit this maturity. Some are in a much younger stage of erosion, and a few are very young indeed. Obviously, therefore, the mountains are of different ages. In general, however, the region as a whole exhibits a stage of erosion nearer the hypothetical end of the arid cycle than do most parts of the southwestern desert region. In other words, it has been relatively stable in recent geologic time. Movements have taken place in it, but they have not been numerous or profound. Compared with the region north of the fault it is certainly stable.

This region of indefinite structural trends and relative stability south of the Garlock fault is a part of Mohave Desert. This fault thus forms the natural northern boundary of the desert, just as the San Andreas rift forms a part of its natural southern boundary. Thus the western part of the desert is a wedge-shaped area lying between these intersecting faults. This feature stands out clearly on the geologic map of North America, where the western Mohave Desert has the appearance of a great arrow-head whose tip is driven westward into the belt of rocks that form the Sierra Nevada and Peninsular ranges. Beyond the fact that the arrow-head is a relatively stable area lying between two great active intersecting faults, the significance of the feature is not yet known.

In tracing the Garlock fault east of the Randsburg quadrangle the party made five traverses across the fault, each traverse spaced at intervals of about ten miles. It was found that the fault is bordered by a zone of roughly parallel branching faults much like the zone that borders the San Andreas fault. At most places this zone is made up of long, narrow, sliver-like blocks resembling those which characterize the San Andreas rift. The pre-Tertiary rocks along the fault wherever examined are thoroughly crushed and brecciated. Much of the breccia is cemented by silica. The rocks are not only crushed but are profoundly altered, apparently by hydrothermal agencies. The schists and gneisses are so changed that their outcrops resemble those of bright-colored Tertiary clay beds and are apt to be mistaken for them unless one examines them closely. In places this zone of hydrothermally altered rocks is as much as a mile wide.

It is evident that the fault is a major line of weakness upon which movements have been taking place through several periods of geologic time. Probably the first movements were pre-Tertiary. The study was not sufficiently detailed to determine the nature of the movements, or their dates, for no fossils were obtained which would fix the age of the Tertiary and Quaternary beds involved in the faulting. Hulin, however, has shown that in the Randsburg district the movements along the fault were chiefly horizontal, and he believes that the major faulting took place in Quaternary time. In the area which was studied no features were found so extremely recent as those which characterize the San Andreas fault, but the fact that these features do occur along the fault in the area studied by Hulin shows that the fault is still active. It differs from the San Andreas fault in that the areas of recent activity are not continuous throughout the length of the fault.

Death Valley fault and the Panamint Valley fault.—Two other faults were examined: the fault which forms the stupendous escarpment along the east side of the deep middle part of Death Valley between Furnace Creek and Mormon Point—the Death Valley fault; and that which forms a similar escarpment along the east side of Panamint Valley between Wildrose Canyon and Wingate Pass—the Panamint Valley fault. They are interesting because they exhibit evidence of movements as recent as those which have taken place upon the San Andreas rift, because parts of their huge scarps are fresher than any other scarps of similar magnitude in the West, and because they exhibit a number of peculiar features whose significance is not yet understood. These faults deserve the closest study. When they are better known to geologists they will undoubtedly constitute one of the classic geologic features of Western America.

The Death Valley and Panamint Valley faults are so similar that a general description of one may be applied equally well to the other; they are twin features having a common origin. Each fault determines an escarpment thirty-five miles long which at some places is more than a mile high. The escarpments of the two faults are twenty-five miles apart and are roughly parallel, trending slightly west of north. Each escarpment is an exceedingly rugged, bare, sloping rock-surface that rises abruptly from the valley floor. At most places the profile of this rock-surface exhibits three elements. At the base, along the valley floor, is a small vertical cliff, a set of cliffs, or a greatly oversteepened slope; at some places attaining a height of over one hundred feet; at other places absent. This cliff marks a recent fault or

set of faults. The planes of these faults where exposed in the bedrock are nearly vertical. Some of the faulting is so recent that it has displaced fresh talus heaps along the cliff. Above the small vertical cliff the escarpment rises several thousand feet in an extraordinary huge sloping surface whose angle of slope averages thirty-five degrees. This surface is scored by innumerable parallel ravines which run straight down it to the valley. These gullies are deep, straight, and acutely V-shaped. Many of them are mere vertical slots in the rock. The surface resembles that of a typical fault facet, but unlike fault facets, which only truncate spurs, it is continuous. One would like to call it a fault-face. It gives the impression of extreme topographic youth, for, when viewed from a distance, it suggests a freshly made, sloping clay bank in a railway or road cut that has been ripped by innumerable small parallel gullies in a single torrential rain. One who views the surface from a distance finds it difficult to avoid the impression that it represents a dissected fault-plane. Above the gullied or "ripped" surface just described, the slope of the escarpment becomes much gentler, changing to about twenty-five degrees. Wide valleys with broad mouths open out at the top of the thirty-five-degree slope, and the topographic forms become relatively subdued and rounded. This maturer topography characterizes all the mountain range about the thirty-five-degree rock-face.

Obviously, the escarpment is the result of more than one earth-movement. The major movement is recorded in the huge thirty-five-degree rock-face, and the relatively mature topography above this rock-face is the pre-fault topography. More recent movements are recorded in the small cliff that meets the valley floor at the base of the sloping rock-face; and still more recent movements, which undoubtedly are still in progress, are recorded by scarps in the recent alluvial fans at the base of the cliff. A noteworthy feature of the escarpments of the Death Valley and Panamint Valley faults is the utter insignificance, and, at places, absence of alluvial fans along their base. At most places the playa flat or salt marsh that occupies the deepest part of each valley lies directly against this escarpment along its eastern margin, as is shown by the fact that all the small ponds which constitute the sinks of the valley drainage occur directly at the base of the escarpment. The fans on the opposite side of the valley present the strongest contrast. They are enormous features which border all the west side of each valley in a continuous alluvial apron several miles wide.

At some places remnants of alluvial fans that are vastly older and were once far larger than the present insignificant fans lies along the escarpments, some reaching to considerable height above the valley floor. These remnants, most of them masses of coarse fanglomerate, are deformed, faulted, and dissected. As a rule they occur in great embayments, or "bights," in the escarpments, to be described later. At one place in Death Valley, a few miles south of Mormon Point, a huge scar on the escarpment marks the place where one of these ancient alluvial fans once rested against the escarpment. All that now remains of the fan are some dislocated and dissected masses of fanglomerate at the base of the scar. At places in both Panamint and Death valleys, distinct sets of shore lines marking several levels of a lake that once existed in each valley are preserved on these dissected remnants of old alluvial material. The remnants of older fans just

described are further evidence that more than one period of faulting was involved in the production of the escarpments.

Several considerations suggest, although they do not prove, that the slant of the thirty-five-degree rock-faces that form the lower part of the escarpments is not far from the slant of the plane of the fault which determined each rock-face, if, indeed, the rock-face does not actually represent the dissected fault-plane. Everywhere in Panamint and Death valleys these rock-faces are remarkable for the fact that the rocks which compose them—chiefly pre-Cambrian gneisses and schists with some metamorphosed Paleozoic rocks—are so crushed, shattered, and sheared that they are virtually fault gouge. The shearing planes in this crushed material, at the few places where the author has had a chance to observe them, are nearly parallel with the slant of the rock-face.

The insignificance or absence of alluvial fans at the base of each rock-face is also suggestive. If the rock-face does not owe its uniform thirty-five-degree slope to the fact that it coincides roughly with a fault-plane, but, rather, to the fact that it was formed by retreat under erosion from a steeper fault at its base, one would naturally expect to find the eroded material forming large fans at the base of the escarpment. Yet no large fans exist there.

Without more detailed study the author does not wish to assert that these rock-faces actually represent fault-planes, but believes they more strongly suggest that relation than any scarps of similar magnitude in the West.

The date of the faulting represented by the great slanting rock-faces along the Panamint Valley and Death Valley escarpments is probably early Quaternary, but it cannot be determined definitely until the rocks along the escarpments are studied in detail.

In many ways the Death Valley and Panamint Valley faults differ conspicuously from the San Andreas rift and its counterpart, the Garlock fault. Unlike the San Andreas rift, whose topographic expression is pre-eminently longitudinal valleys and which is not marked everywhere by strong and persistent vertical inequality of the rock-masses on opposite sides of the fault, the Death Valley and Panamint Valley faults are marked by strong and high escarpments which face consistently in one direction. They are the result of vertical movements of great magnitude and are normal faults. They are counterparts, rather, of the great fault along the eastern face of the Sierra Nevada, and of the fault along the west side of Saline Valley, both of which they greatly resemble. Their escarpments, however, are much fresher than that of the Sierra Nevada fault. They differ also in pattern from the San Andreas fault. The San Andreas fault itself is remarkably straight and is continuous. The Death Valley and Panamint Valley faults, on the contrary, are exceedingly irregular in detail. Neither is a straight, continuous fault; they are, rather, a succession of faults, each of which is offset from the other along the strike. Consequently their escarpments have a roughly zigzag pattern and are indented by great concave bights or cusps where the offsets occur. At some places the bights mark cross-faults; at others they appear to represent areas of great and sudden downwarp. At many places the faults exhibit enormous changes in amount of throw in distances of a few miles. Actually the rock-masses in the escarpments along the Death Valley and Panamint Valley faults are a series

of tilted crustal blocks which have been displaced very irregularly and unevenly. The escarpment of the Death Valley fault at Mormon Point, for example, is the face of a crustal block that emerges from the valley floor at Mormon Point and rises southward so rapidly that it attains a height of several thousand feet within three miles south of the point. The escarpment of the Death Valley fault as a whole is made up of at least four tilted crustal blocks like the one at Mormon Point. Each block is tilted north at right angles to the strike of the main fault. In brief, the structure along these great faults is astonishingly complex and the history of the different movements that have taken place is far from simple.

The Death Valley and Panamint Valley faults resemble the San Andreas rift in exhibiting evidence of very recent movements at many places. Some of the most recent fault features, indeed, are no less striking than those along the San Andreas rift. The author has already described the small discontinuous cliff that appears at many places along the base of the escarpments of the Death Valley and Panamint Valley faults. This cliff is certainly the result of recent faulting. The most striking evidences of recent movement, however, are vertical scarps which displace many of the small alluvial fans at the base of the escarpments. Each scarp crosses a fan in a direction at right angles to the slope of the fan, faces the valley, and usually lies near the apex of the fan. The scarps are parallel with the great escarpments back of them and lie very near the escarpments. In Death Valley the author counted five fans displaced by these fault scarps and in Panamint Valley, seven. Probably others exist in both valleys. Some of the scarps are as much as twenty feet high. They must be very recent features indeed, for even in that dry region they could not stand up long in the unconsolidated materials that make the fans.

Perhaps the most impressive recent fault feature, although it is somewhat older than the small fault-scarps just described, is a huge fault-trench, or "graben," gashed across a great fan at the mouth of Wildrose Canyon in Panamint Valley. This fan, which lies near the northern end of the Panamint Valley fault-scarp, is composed largely of older Quaternary alluvial deposits. It has not been depressed or wrecked by faulting and erosion, as have many of the other old fans. The trench runs straight across the fan from north to south at right angles to the slope of the fan. It lies parallel with and near the Panamint Valley fault-scarp and undoubtedly marks a movement along the line of that fault. It is a colossal feature, four miles long and a mile wide. At places the bordering scarps attain a height of four hundred feet. The main drainage channel of the fan follows the trench almost to its southern end, finally breaking out through a deep gorge cut through the western escarpment of the trench. Two gaps in this escarpment at points higher up on the fan have been occupied in turn by the drainage channel. Each was abandoned when renewed faulting deepened the trench and increased the height of the western escarpment.

A similar trench near the base of the escarpment of the Panamint Valley fault crosses a fan that lies four miles north of the mouth of Goler Wash. This trench, however, is much smaller than the one just described. The fan which it crosses is an old one, because the granite boulders of which it is composed are all rotten and exfoliated, whereas the present material issuing from the canyon back of the fan is all fresh.

This effort of the Committee to direct attention to the subsurface structure in the zone of greatest weakness in California is co-ordinated with a like effort to fix the present surface configuration in both horizontal and vertical dimensions by adequate primary triangulation and precise levels in the zones thought to be subject to future displacement. Such surveys of the highest precision have been carried out by the United States Coast and Geodetic Survey during the same period of years and it is appropriate that the progress of the work be considered side by side with the geological investigation presented above.

The report was prepared by Major William Bowie, Chief of the Division of Geodesy of the United States Coast and Geodetic Survey.

GEODETIC WORK IN REGIONS OF SEISMIC ACTIVITY EXECUTED BY THE UNITED STATES COAST AND GEODETIC SURVEY³

During the fiscal year ending June 30, 1926, the United States Coast and Geodetic Survey continued geodetic operations in California under the appropriation made by Congress for this specific purpose. An appropriation for this class of work was first made in 1923 and has been continued yearly since, though there has been a gradual reduction in the amount from \$15,000 per annum to \$10,000 per annum.

Triangulation was done in three places. The first work was along the 39th parallel beginning with the stations Mount Lola and Round Top and working eastward for 115 miles and ending on the stations, Carson Sink and Mount Grant. This work was thought to be necessary by the Committee on Seismology of the Carnegie Institution and the officials of the United States Coast and Geodetic Survey because Mount Lola and Round Top are considered to be in a region that may be unstable geologically speaking, while the triangulation stations 115 miles to the east of those two stations are located in a region that is supposed to be entirely quiescent.

This triangulation on the 39th parallel indicated that there had been no radical changes in the angles since the original observations in 1878 and 1879. The largest change in any one angle was only 0"74, which is within the range of the probable errors of the observations.

When the triangulation party had finished the work on the 39th parallel it shifted to the vicinity of Ukiah, California, where triangulation was done to connect the variation of latitude station at that place with the first-order triangulation along the 39th parallel. This connection was made and then certain stations to the westward of Ukiah were occupied and a connection made between the first-order triangulation and the third-order triangulation stations which are along the California coast.

³ By Dr. William Bowie. Printed by permission of the Director of the United States Coast and Geodetic Survey.

When the Ukiah triangulation was completed, the party moved to the vicinity of Santa Barbara Strait where six stations, which had been occupied by a party in 1924, were reoccupied. The 1924 work was not entirely satisfactory, owing to the fact that the work had to be hurried due to the exhaustion of funds, and the stations were left before a sufficient number of observations could be made to secure the requisite accuracy in the angle measurements. The reoccupation of the Santa Barbara stations in 1925 furnished excellent closing errors.

It may be mentioned in passing that a comparison of the 1925 with the 1924 angles along the Santa Barbara Channel did not indicate any material shift of the geographic positions for the stations involved during the year which elapsed between the observations. The stations involved are Tepusquet, Lospe, Gaviota, Arguello, Santa Cruz West, and Santa Barbara. The greatest difference in an angle between the 1924 and 1925 measures was $3''24$, and the observations of 1924 were known to be in error.

Leveling of the first order was executed under the appropriation for "geodetic work in regions of seismic activity" in Owens Valley and on the eastern slope of the Sierra Nevada. At the beginning of the season it was the intention of the officials of the Coast and Geodetic Survey and the members of the Committee on Seismology of the Carnegie Institution to have a line of first-order leveling extend across Owens Valley and up to the summit of Mount Whitney. A line of levels by the United States Geological Survey had been run to that peak some years ago, and it was believed that a re-running of that line would be of interest and value in showing whether or not Mount Whitney is changing its elevation with relation to the floor of Owens Valley.

Unfortunately, the leveling party found that the Mount Whitney trail had been destroyed in many places and it was impossible to use animals to pack the camp equipage, instruments, and food to points where camps would have to be made. The party was on the peak for a few days, but it soon became evident that little or nothing could be accomplished and the expense involved in running a line of levels without a trail would be excessive. The chief of the party, Lieutenant Simmons, telegraphed to the Director of the Coast and Geodetic Survey, describing the conditions of the trail and recommending the abandonment of the line. His recommendation was approved and he was directed to extend the line of levels from a point at an elevation of about 8,373 feet on the old trail eastward across Owens Valley to a point on the Inyo Mountains at an elevation of approximately 1,000 feet above the valley floor. This work was successfully accomplished by the leveling party. Numerous bench marks of a substantial nature were placed along the line.

The Coast and Geodetic Survey from its regular appropriation executed other leveling in California which will be of service in connection with earthquake studies in the future. A line of first-order levels was run from Laws, California, southward through Owens Valley to Mojave. This line was tied into the line which was run across Owens Valley.

Other leveling in Los Angeles County was run by the Coast and Geodetic Survey in connection with mapping and engineering operations in that county. This work was done in co-operation with the Geological Survey.

It may be of interest to those who are making seismology studies to know that the Coast and Geodetic Survey under its regular appropriations for geodetic work is to extend in the fall of 1926 an arc of first-order triangulation from the vicinity of San Luis Obispo across the Sierra Nevada Mountains and Death Valley to a junction with the triangulation which extends from Needles, California, northward to the transcontinental triangulation in Utah. This arc will be of service in the extension of triangulation over active seismic regions in California.

During the past year the Coast and Geodetic Survey in its office in Washington has been making a readjustment of the whole triangulation net of the western half of the United States. This adjustment will take into account all of the triangulation from the arc along the 98th meridian to the coast. For many years it has been necessary to fit new triangulation into the old, which was held fixed by previous adjustment; but with the breaking up of the great western areas by new arcs of triangulation, it was found that a new adjustment of the net work as a whole should be made. A plan devised by Dr. William Bowie, Chief of the Division of Geodesy, details of which were worked out by Dr. O. S. Adams of that Division, was put into effect and during the past year an average of about eight mathematicians have been on this work. The final geographic positions of the junction points of the various arcs will become available shortly after the close of the field season in the fall of 1926. The work done during that season will be included in the net adjustment. It is expected that shortly after the completion of the adjustment of the net of the western half of the country, which will give the final positions for junction points, a further study of the new and old triangulation of California will be made. Pending that time, it is believed by the officials of the Coast and Geodetic Survey to be inadvisable to try to interpret the changes in geographic positions resulting from the new triangulation.

It is expected that during the fiscal year ending June 30, 1927, the geodetic work done under the appropriation for seismic regions will consist largely of first-order leveling executed in southern California, according to a plan which was outlined by the Committee on Seismology of the Carnegie Institution and approved by the officials of the Coast and Geodetic Survey.

PUBLICATIONS

The Committee has continued to administer during the past year the grant of \$5,000 provided by the Carnegie Corporation of New York in aid of seismological publication. Eight reports of recent seismologic research, including the full "Description and Theory of the Torsion Seismometer" by Anderson and Wood, have been printed in the BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA, either wholly or partly at the expense of this fund, which has been of the greatest service to seismology in its hour of need. Amount expended, \$2,123.75; available balance, \$1,641.04.

DEVELOPMENT OF INSTRUMENTS⁴

At the end of June 1925, we were at work upon a method for rotating and advancing the recording drums for our seismometric assemblies accurately and at moderate cost. The progress of this work up to that time was set forth in detail in the last previous report. Work upon this has been continued during the present year and as a result a satisfactory and reliable system and mechanism have been developed.

Among numerous alternative ways of improving this method which were mentioned in the last report, two were emphasized as especially important: (1) the use of a temperature-controlled vibrating spring, reed, or tuning fork to regulate the frequency of oscillation, in place of an inductance-capacity oscillator-system; and (2) the operation by the oscillator-system of two relays in a quarter-phase relation so as to supply quarter-phase impulse-current to quarter-phase impulse synchronous motors, thus to insure self-starting under normal load with uniform rotation always in the same direction. Both these desired developments have been carried through successfully and are incorporated in the mechanism as it is to be used. At the same time the size of the motors has been reduced, and their current consumption also, and their construction has been reduced in cost by changes in design with the use of easily worked soft iron parts in place of steel laminations. These motors now operate satisfactorily on one-fourth of a watt each.

The synchronous motors operate gear-work which is constructed to run in oil, and is so designed that by a change of gear wheels, which may be made conveniently, the speed of rotation of the recording drums can be made 60, 30, 15, or 7.5 mm. per minute. Under well-controlled conditions we have attained an accuracy of one part in one hundred thousand over an interval of twenty-four hours.

In its present form the recording assembly is an accurate and convenient mechanism of excellent design, but further improvements are considered practicable.

Work is now in progress in standardizing the design of the vibrating reed or fork member of the oscillator-system, which has succeeded so well in the experimental testing.

For driving slowly rotating drums accurately to serve in teleseismic recording, a ratchet motor operated by a simplified reed-oscillator system is under consideration. This will operate through a suitable gear-work with ten, say, driving impulses per second. Since, *with slow rotation*, such step-by-step motion at very short intervals can be tolerated, cost can be saved in construction without sacrifice of accuracy. This development will be undertaken as soon as opportunity offers.

High input-impedance electron tubes have now been developed abroad. An effort to obtain these has been made and is now pending. If these prove to have suitable characteristics we may be able to develop a practical piezo-electric accelerometer—an assembly which should afford a sensitive element of exceedingly short proper period which yet possesses adequate means of magnification to offset its low intrinsic sensitiveness. Such tubes may also prove of service in the development of electrical displacement meters. If these electron tubes are obtainable these experiments will be carried out as early as opportunity can be found.

⁴ Extracted from the report of H. O. Wood, Research Associate in Seismology.

The problem of providing conveniently and at suitable cost light-sources brilliant enough and enduring enough for the photographic registration of large amplitudes in the case of local earthquakes in which the vibration is comparatively rapid, with recording drums rotating at the rate of sixty millimeters per minute, has proved even more difficult than was anticipated. With a sufficiently brilliant small source, having adequate life and economy of operation, the method in which this source is interrupted by a rotating disk, from which proper sectors have been cut out, would be practical. It has proved difficult to find a light-source suitable for continuous operation on this principle. Self-interrupting sources, such as mercury vapor lamps, low-pressure nitrogen and helium tubes, etc., have been tried, with various modifications. It is possible that success will be achieved with one of these, but the outlook is not entirely encouraging. It is possible to conduct registration with present resources, of course, but marked improvement is very greatly to be desired and every effort will be made to find the best practicable solution of this problem.

The theory and design of seismometers to register the *energy* of an earthquake at the station has been the subject of much thought and consideration. As soon as it becomes practicable, experiments will be made with this end in view. Three types of energy-recording instruments are under consideration, one to register the kinetic energy, one to register the potential energy, and one to register the integrated energy.

Up to the present our shop resources have been too limited to enable us to carry on our experimental work as uniformly and rapidly as desirable. It is hoped that this situation will be improved somewhat because of the opening of a shop by Mr. F. C. Henson, who has given up his other activities to engage in this undertaking. During the year under report Mr. Henson has been licensed to manufacture our seismometers and auxiliary apparatus. This venture is still new and work on orders for apparatus is necessarily still taking precedence over work on experimental apparatus.

Work on the development of radio minute-to-minute time signals was begun late in the year under report, after the development of the recording system had been brought to a practical point. This is a task of great importance and considerable magnitude and it will require time for its practical accomplishment. However, it has been found already that the production and sending of a signal of very considerable power is practicable at much less cost than early estimates indicated. Problems connected with the receiving and recording of these signals and the reduction and sufficient elimination of interference are yet to be undertaken.

We have continued to operate torsion seismometers under varying experimental conditions on the two piers available at the Observatory Office and the one available at the Norman Bridge Laboratory of Physics at the California Institute of Technology. There have been interruptions in this operation, affecting chiefly one instrument at a time, due to experimental changes, necessary reconstruction work, and the work of re-installation. Many earthquakes have been recorded, both distant and local in origin, including, of course, the large number of aftershocks of the Santa Barbara earthquake of June 29, 1925.

As a result of experimentation with this apparatus we have found it possible

and practicable to register teleseisms at a recording distance of forty centimeters with static magnification of about 160, thus obtaining a very fine photographic line on the seismogram. Under more convenient working conditions we expect to obtain a still finer line at a recording distance of only twenty centimeters with a direct static magnification of only 80. The aim of this experimental work is to secure an assembly, for teleseismic purposes, which will operate satisfactorily for a week with only one loading.

By re-shaping the pole-pieces of the damping magnet of the seismometer and winding them with wire, it has been found practicable temporarily to reduce or neutralize the field of the permanent magnet so that the free, proper period of the seismometer may be determined more conveniently and without risk of any change in adjustment such as may be caused by lowering and raising the magnet, which procedure is otherwise necessary in order to redetermine the free period where this device is not available.

Other minor improvements in design and construction have been worked out in connection with the optical system and the mirror fastenings.

The earthquakes registered during the year under report, including the shocks of the Santa Barbara series, have been measured in the systematic routine way.

All significant results of this measurement will be the subject of further study, after which the matter will be published in appropriate form. In this connection, however, it should be pointed out that all this registration has been conducted under experimental conditions which are quite adverse in several respects. Hence report upon the measurements of these shocks in the standard tabular form will very likely prove inadvisable.

In the course of routine the numerous aftershocks of the Santa Barbara event have already been measured in the ordinary way. They have been the subject of considerable further special study. The registration of these shocks, with open scale recording, critical damping, and high static magnification, presents many marked characteristics not usually encountered. These demand careful consideration, so that the investigation of these shocks is in no sense complete. The detailed study of these records, together with the study of records of the chief shock written at distant stations, will be undertaken in co-operation with Dr. Perry Byerly, of the University of California.

We have once again recorded at Pasadena the shock due to a great blasting operation; 62.5 tons of dynamite, it was reported, were set off as a single charge in a limestone quarry at the place named Monolith situated in the Tehachapi Pass about seventy miles north, and a little to the west, from Pasadena. The shock of this blast was recorded unmistakably even by the seismometer adjusted to have the least static magnification, but the distinctions of phase were not satisfactorily well marked. This is due probably to the dissipation and modification of the originally small energy after traversing a path more than seventy miles long.

RESEARCH LABORATORY AND SUB-STATIONS

In the Report of last year announcement was made of the generous provision by the California Institute of Technology for a new laboratory

building to house the research work in seismology of the Carnegie Institution of Washington and such co-operative studies as might be agreed upon, and to serve as a central station for the system of outlying stations now under construction.

The laboratory building was described in considerable detail last year (*Year Book No. 24*, pp. 377-78). Minor delays occurred in the construction work but the building is now completed, including a garage and living room for an assistant, and at the time of writing the system of electric wiring is being installed. It is expected that the building will be occupied within a few weeks. It is most conveniently located and arranged and will serve its purpose admirably.

The station built by the city of Riverside is completed and the instruments are being installed. Both the Central Station at Pasadena and the sub-station at Riverside enjoy most favorable locations on crystalline rock. The station at La Jolla is to be located in one of the basement rooms of the Scripps Oceanographic Laboratory, which has been especially prepared for this purpose. This laboratory is located directly on the beach at La Jolla and will afford an opportunity, novel for this branch of science, to study the effect of sea-waves in altering or modifying seismic impulses from outside. The location is to this extent something of an experiment. At the time of writing the instruments for this station are completed and are being tested before final installation. It is expected that instruments will be recording in these two branch stations and in the Central Station at Pasadena before the close of the year.

Two other stations which have been mentioned before are now under construction; one on Mount Wilson in connection with the Mount Wilson Solar Observatory, the other at Santa Barbara in the grounds of the Museum of Natural History. The Santa Barbara station was provided through the generosity of a number of public-spirited citizens of that city, and now that arrangements are completed in full detail, construction is expected to proceed rapidly. At Santa Barbara also a somewhat unusual foundation has been encountered. It consists of water-laid boulder gravel, several hundred feet in thickness, well-consolidated, practically impervious to water, and probably quite serviceable for this purpose. Nevertheless the outcome of such an installation must be accounted somewhat experimental. The location on Mount Wilson is on crystalline rock.

Other stations which have been considered and reported on previously have not advanced beyond the negotiation stage.

SAN FRANCISCO BAY STATIONS

Through the activities of Dr. Willis of this Committee a plan has been developed for an independent group of stations about San Francisco Bay, which is likely to be realized in the immediate future. The group includes stations at the University of California (Berkeley), the Lick Observatory (Mount Hamilton), Stanford University, and Golden Gate Park (San Francisco). On all of these stations construction is to be begun at once and instrumental equipment identical with that provided for the stations of the Carnegie Institution is to be installed as soon as it can be built. These stations will be conducted under the direction of Professor Byerly of the Department of Seismology at the University of California, in close co-operation with the stations of the Carnegie Institution in the south. It is most fortunate for the study of earth movements in the west-coast region that both centers of recent seismic activity are to be so completely equipped for the study of these movements at an early date.

PATENTS

Recent activities in oil-field exploration by methods involving the seismograph or pendulum principles have had the effect of making certain classes of instruments unavailable for ordinary research work. Some types are not now on the market at all, and those which are obtainable are subject to conditions which make it extremely difficult to obtain either the instruments themselves or data concerning their performance. It has therefore been deemed wise to protect the Wood-Anderson seismograph, which has been developed by the Carnegie Institution for this research, by suitable patents. These patents have already been issued and a manufacturer has been licensed to make the instruments upon specifications authorized by this Committee and to market them on terms which will insure their availability for similar research elsewhere.

RECOMMENDATIONS

It is recommended that provision be made:

1. For further experimental work on vertical-component instruments for the stations already designated.
2. For the further study of minute-to-minute time signals for simultaneous record at all of the stations.

3. For further experimental work in the study of cumulative stresses (tilt mechanism).

4. For two additional branch stations at appropriate points north and west of Pasadena.

J. A. ANDERSON

RALPH ARNOLD

J. P. BUWALDA

W. W. CAMPBELL

ARTHUR L. DAY (*Chairman*)

A. C. LAWSON

R. A. MILLIKAN

HARRY FIELDING REID

BAILEY WILLIS

Advisory Committee in Seismology